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A Study to Model the Effects of Uranium Mine Tailings on a Permafrost Environment

Northern Affairs Program

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TABLE OF CONTENTS

	Page
Executive Summary	i
Resume	iii
Acknowledgements	v
1. INTRODUCTION	1
1.1 Background	1
1.2 The Objective	2
1.3 The Approach	2
2. URANIUM TAILINGS DISPOSAL	5
2.1 Physical Properties of Tailings	5
2.2 Disposal Methods	6
2.2.1 Valley Dam Impoundment	6
2.2.2 Ring Dyke Impoundments	7
2.2.3 Mine Pit Impoundments	7
2.2.4 Specially Dug Pits	8
2.2.5 Underground Mine Impoundment	8
2.2.6 Deep Lake Impoundment	8
2.3 General Control Measures	8
2.3.1 Geologic Liners	9
2.3.2 Control of Hydraulic Gradient	9
2.3.3 Tailings Management	9
2.3.4 Rehabilitation	10
2.4 Possible Effects on a Permafrost Environment	10
2.5 Impact Estimation and Regulation	12
3. STUDY AREA AND FIELD METHODS	14
3.1 District of Keewatin	14
3.2 Lone Gull Site	17
3.3 Field Methods	18
4. THE COMPUTER MODEL	20
4.1 Tailings Not Underwater	20
4.2 Subaqueous Tailings	22
4.3 Flow Diagram for the Model	23

Page

5. MODEL APPLICATION 27

5.1 Model Testing 27
5.2 Effects of Tailings Management Strategies 31

6. RECOMMENDATIONS 38

6.1 To the Proposing Mining Company 38
6.2 To the Regulatory Agency 39

REFERENCES 40

Editorial Notes: Lone Gull is now known as Kiggavik.

Copies of the Computer Program are available from Mining Management and Infrastructure Division, Department of Indian Affairs and Northern Development, Ottawa, K1A 0H4.

EXECUTIVE SUMMARY

Uranium mine tailings may have long-term environmental impacts because of their low radioactive decay rate, but little is known about the effect of such tailings on the arctic environment which is fragile to certain aspects of development. It is desirable to minimize the release of the contaminants so that the toxic and radioactive materials will not be transported through the environmental system. Problems related to the disposal of uranium mine tailings are similar to those associated with wastes from other metal mines, but again there is a lack of information on their interaction with the northern environment.

A reduction of the risk of escape of contaminants is best achieved by isolating the tailings: by diverting the surface inflow around the tailings; by protecting the tailings against wind scour; by eliminating groundwater discharge; and by containing the incident precipitation or treating the water before release. Although the principle is simple, in practice, it is necessary to know the magnitudes of the various hydrologic and thermal processes acting upon the tailings to minimize the outward transport of contaminants. In the absence of previous information on uranium mine tailings in a permafrost setting, it is desirable to use a computer modelling approach which allows various tailings control strategies to be tested economically. The model should be operative given a limited amount of meteorological data that is generally available in such a remote area as Central Keewatin where ore bodies of economical quantity have been discovered. Thus, **the objective of this study is to establish a model to describe and predict the effects of uranium mine tailings on the hydrological and thermal environments of the tundra permafrost in Keewatin.**

This study began after a field reconnaissance in 1981. Two years of major field investigations, carried out in Central Keewatin, allowed various requisite equations and parameters to be determined for the model. The one-dimensional model for a vertical column of the tailings simulates the daily temperature and moisture profiles using inputs of air temperature, precipitation, solar radiation and lateral inflow to the tailings. If the tailings are flooded, the model will also simulate the ice cover and the effects of the floodwater upon the thermal regime of the tailings. One major feature of this model, not present in most other existing hydrologic models, but crucial for permafrost areas, is the coupling of the water and energy fluxes. Energy is used to melt the snow, evaporate the water, and through thawing of the active layer, provide storage capacity for the groundwater. Water and ice distributed within and on the tailings affect the surface albedo, the thermal

properties of the soil which in turn alters the rates of heat conduction, frost penetration and thawing front propagation. A thick frozen zone will ensure that there is little groundwater leakage, but the lack of storage capacity for groundwater often leads to surface outflow that may transfer the contaminants out of the tailings. A modification of the tailings structure will affect the hydrologic and thermal properties and, consequently, the water and heat flow regimes.

Detailed descriptions of different components of the model are given in the programmer's manual which also includes a program listing and a definition of the parameter values. The user's manual describes the data file, the interactive input session and provides sample outputs from the model. The model was satisfactorily validated by comparing the simulated results against field observations of water table and frost table changes at the field study site. Simulations were then performed to test the effects of altering the tailings structures and of increasing the snow cover thickness, a common situation when the tailings are emplaced in topographic depressions. The presence of a peat cover on the tailings is found to reduce the annual thaw depth; and heavy snow accumulation will generate considerable outflow. These tests are by no means exhaustive but demonstrate the ability of the model to quantify the magnitude and timing of the hydrologic and thermal responses, given various tailings management strategies.

It is recommended by our study that the model should be applied to each specific proposed tailings site to test the possible impacts of various tailings emplacement strategies, using long-run climatic data from weather stations but adjusted to the tailings location. It is further recommended that the model can be applied to tailings other than those of uranium and therefore, it can be used for any mining development in a continuous permafrost setting.

RÉSUMÉ

Les résidus des mines d'uranium peuvent avoir des conséquences à long terme sur l'environnement à cause de leur faible vitesse de désintégration radioactive, mais on connaît peu de chose sur l'effet de ces résidus sur l'environnement arctique qui est fragile à certains égards. Il est souhaitable de minimiser le rejet de contaminants de façon à éviter que des matières toxiques et radioactives ne soient disséminées dans l'environnement. Les problèmes liés à l'élimination des résidus des mines d'uranium sont semblables à ceux associés aux déchets d'autres mines de métaux, mais là encore on connaît mal leur interaction avec l'environnement septentrional.

Le meilleur moyen de réduire le risque que des contaminants ne s'échappent dans l'environnement consiste à isoler les résidus : en déviant les écoulements de surface autour des résidus; en protégeant les résidus contre l'érosion éolienne; en éliminant les fuites souterraines; et en captant les précipitations incidentes ou en traitant l'eau avant de la rejeter. Même si le principe est simple, il faut dans la pratique connaître l'ampleur des différents processus hydrologiques et thermiques qui agissent sur les résidus pour minimiser la dissémination des contaminants. En l'absence d'information recueillie antérieurement sur les résidus des mines d'uranium dans un environnement de pergélisol, il est souhaitable de recourir à une modélisation sur ordinateur qui permet d'essayer de façon économique différentes stratégies de contrôle des résidus. Le modèle devrait être fonctionnel avec une quantité limitée de données météorologiques qui sont en général disponibles dans des régions aussi éloignées que le centre du Keewatin où des corps minéralisés exploitables ont été découverts. Ainsi, l'objectif de la présente étude est d'établir un modèle pour décrire et prévoir les effets des résidus des mines d'uranium sur les environnements hydrologique et thermique du pergélisol de la toundra dans le Keewatin.

La présente étude a été entreprise après une reconnaissance sur le terrain effectuée en 1981. Deux années de recherches intensives sur le terrain, menées dans le centre du Keewatin, ont permis d'établir différentes équations et paramètres nécessaires au modèle. Le modèle unidimensionnel d'une colonne verticale de résidus simule les profils quotidiens de température et d'humidité à partir de données sur la température de l'air, les précipitations, le rayonnement solaire et les flux latéraux entrant dans les résidus. Si les résidus sont inondés, le modèle simulera également la couverture de glace et les effets des eaux de crue sur le régime thermique des résidus. Une grande caractéristique de ce modèle, absente dans la plupart des autres modèles hydrologiques existants, mais critique dans les zones de pergélisol, est le couplage des flux hydriques et énergétiques. L'énergie fait fondre la neige, fait évaporer l'eau et, en dégelant la couche active, permet de stocker les eaux souterraines. L'eau et la glace disséminées dans et sur les résidus modifient l'albédo de surface, les propriétés

thermiques du sol qui, à leur tour modifient les vitesses de conduction thermique, de pénétration du gel et de propagation du front de dégel. Une zone gelée épaisse limitera les fuites d'eau souterraine, mais le manque de capacité de stockage pour les eaux souterraines mène souvent à des écoulements de surface qui peuvent disséminer les contaminants à partir des résidus. Une modification de la structure des résidus influera sur les propriétés hydrologiques et thermiques et, par conséquent, sur les régimes d'écoulement hydrique et thermique.

Des descriptions détaillées de différentes composantes du modèle sont données dans le manuel du programmeur qui renferme également un listage du programme et une définition des valeurs des paramètres. Le manuel de l'utilisateur décrit le fichier de données, la séance de chargement interactif des données, et renferme des exemples de résultats produits par le modèle. Le modèle a été validé avec succès par comparaison des résultats simulés contre les variations de la nappe phréatique et du front de dégel telles qu'observées sur les lieux de l'étude. Des simulations ont ensuite été effectuées pour voir ce qui se produit lorsque la structure des résidus est modifiée et lorsque l'épaisseur de la couverture de neige augmente, phénomènes normaux lorsque les résidus sont situés dans des dépressions topographiques. La présence d'une couverture de tourbe sur les résidus réduit la profondeur du dégel annuel et une forte accumulation de neige produira un écoulement considérable vers l'extérieur. Ces essais ne sont aucunement exhaustifs, mais démontrent la capacité du modèle de quantifier l'amplitude et la chronologie des réponses hydrologiques et thermiques pour différentes stratégies de gestion des résidus.

Nous recommandons dans notre étude que le modèle soit appliqué à chaque emplacement spécifique proposé pour l'élimination des résidus afin d'évaluer les effets possibles de différentes stratégies de sélection de tels emplacements à partir de données climatiques à long terme provenant de stations météorologiques et corrigées en fonction de l'emplacement des résidus. Nous recommandons en outre que le modèle soit appliqué aux résidus autres que les résidus d'uranium et que, par conséquent, il puisse être appliqué à toute exploitation minière en zone de pergélisol continu.

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1. INTRODUCTION

1.1 Background

There is potential for uranium mining in the District of Keewatin, and development of the now proven resources will require the establishment of, inter alia, land-use regulations to ensure that it is environmentally acceptable. It is recognized that any mining operation can result in long-term (after close-out) environmental problems generated by tailings deposits as well as short-term (operational) problems. The latter are generally fairly well understood, and health and safety regulations for mining have a long history. The former are, however, much less well understood and are much less general in the sense that the minerals and environment of a particular mine give rise to particular problems. Most new mining proposals must therefore be examined individually for long-term impact, using information that is specific to the proposal.

Little is known about the effects of uranium mining on the arctic environment, which has been shown to be sensitive to some aspects of development. The low concentration of uranium in ore bodies means that considerable volumes of mine tailings will be produced, and their effect will be long-lived. The disposal of these tailings has the potential for serious and long-lasting impacts on the land and water resources and their use.

Relatively little is known about the interior of Keewatin north of the tree-line (the Barren Lands). There are no permanent settlements, and no long-term or continuous records of environmental parameters. In particular there is little information upon which to base estimates of the possible environmental impact of mining. Mines have operated for several years in the boreal forest environment (Port Radium, Yellowknife, Uranium City, northern Saskatchewan) and Cullaton Mines did operate in southern Keewatin. New ventures on the High Arctic coast (Polaris on Little Cornwallis Island and Nanisivik on Baffin Island) are in a considerably different environment from the Low Arctic, and are of little use in estimating long-term effects. Mining in Keewatin north of the tree-line has been limited to the small nickel mine at Rankin Inlet, and the Ferguson Lake mine which never produced. Neither can provide significant information on the possible effects of mining in the Barren Lands.

1.2 The Objective

The objective of this study is to establish a deterministic model to describe and predict the effects of uranium mine tailings on the hydrological and thermal environments of the tundra permafrost in Keewatin.

The modelling approach is taken because:

- large-scale mining has not been undertaken in this environment
- there is little previous information on tailings in a permafrost environment
- there is little meteorological data available, and surface thermal and hydrological properties are not well known
- a model can easily be adapted to different situations by changing the parameters, or to new data
- a model allows proposed control strategies to be tested quickly and economically
- a model is the only way of predicting long-term effects of tailings.

The particular model described here:

- proposes to examine ways to make use of the natural environment to help control tailings
- retains a physical basis and uses readily available input data
- uses parameters that can be measured in the field at the proposed mining site

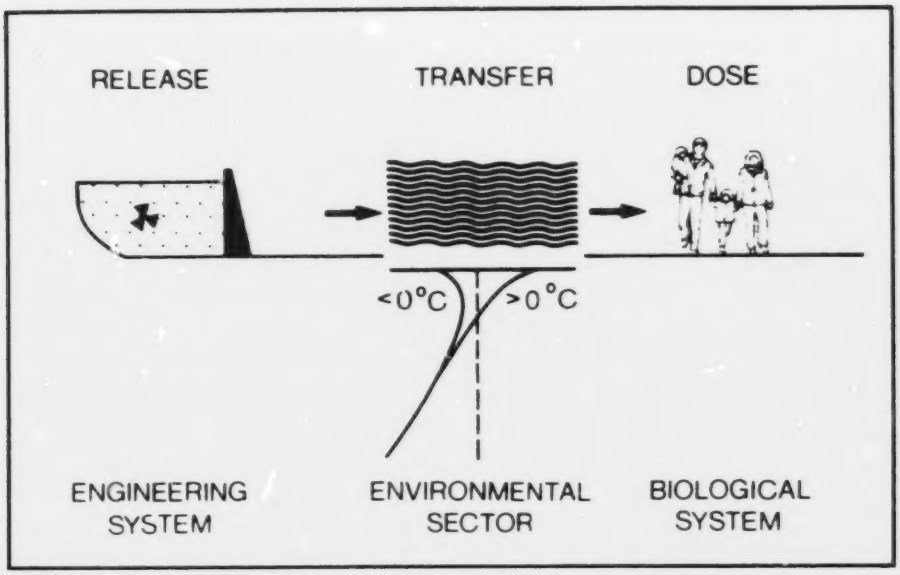
1.3 The Approach

Problems associated with the disposal of uranium mine tailings are similar to those associated with wastes from other metal mines. Although very small doses of radionuclides may be toxic, the proportion of these in any given substance is generally so small that large quantities of contaminated material must be present to pose a hazard (Eisenbud, 1973, Ch. 1). In all disposal situations a distinction can be made between the release of a contaminant, which is subject to engineering control, and its subsequent transport through the environmental system, which is not. It is this latter problem that we consider. Figure I.1.1 shows schematically the distinction, and also that between the short-term period in which release rates may be high and variable and the long-term period in which release rates have settled down to a steady state.

The general environment of any proposed tailings disposal site will be governed by the location of the mine site in Keewatin. The particular disposal environment may, however, be subject to considerable choice because there is a range of

different terrains within reasonable distance of any mine mill location.

In this report we summarize the various uranium mine tailings disposal strategies and their associated problems. We describe the Keewatin environment and the particular problems that it presents to tailings disposal. The modelling approach that we have chosen was justified and the model described. This model was applied to various disposal scenarios. Finally, we present recommendations for the use of the model and the generation of land-use regulations.



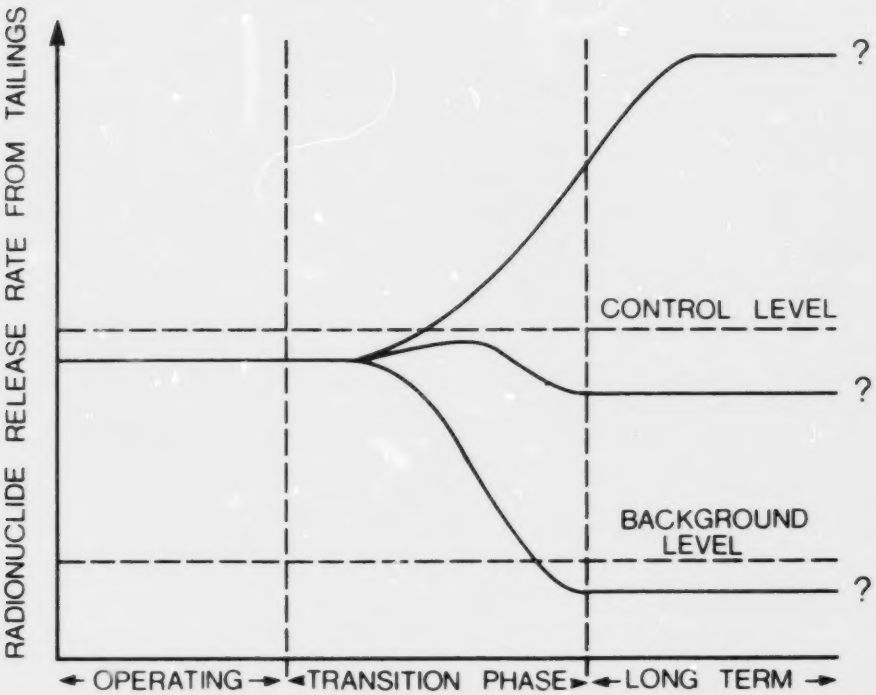


Figure I.1.1: Schematic of radionuclide movement from tailings showing different movement phase (upper) and time scales (lower). (After AECB, 1978).

2. URANIUM MINE TAILINGS DISPOSAL

Tailings consist of the solid and liquid residue from the milling process by which uranium is removed from the ore. They possess the natural chemical and physical properties of the ore bearing rock and those induced by the extraction process. The mining, milling and treatment bring to the surface and mobilise the natural radioactivity and alter other properties of the rock. The exact nature of the tailings is therefore a function of the type of ore, the extraction process employed, and the method of disposal. A combination of these factors and consideration of the environment into which the tailings are being deposited provides a framework for the consideration of their possible effects on the District of Keewatin. The methods of uranium extraction and tailings disposal presented here are limited to present viable engineering practices. In evaluating possible alternative methods of disposal the ease with which future technologies may be able to modify the selected method should be considered. A considerable body of work (e.g. Simpson-Lewis et al., 1983; Bishop and Bishop, 1981; Chakravatti et al. 1982) is available that deals with particular aspects of uranium mine tailings disposal. The particular combination of uranium mine tailings and permafrost has not been previously studied, however, and part of the present research is to determine which previous studies are applicable and which are not.

2.1 Physical Properties of Tailings

Uranium ore is generally processed by one of three methods, depending upon the ore characteristics. The selection of the process is determined by mineralogy, geology and economics. The two major techniques are acid and alkaline leaching. Both techniques require large amounts of chemicals and freshwater. A lesser used process is that of heap leaching which is used for refractory or uneconomical ore bodies.

The acid leach process requires that the ore be crushed generally to less than a 0.5 mm diameter. The acids dissolve large quantities of non uranium radionuclides which can be removed from the ore by sophisticated liquor leach treatments. The resultant tailings are frequently saturated and excess water has to be processed and recycled for use in the milling process. This method recovers large percentages of the available uranium, is easily controlled and needs little power.

Alkaline leaching requires the rock to be crushed to less than 0.075 mm. It selects only the uranium ore and mobilises few unwanted radioactive elements, but the process is more expensive in terms of power requirements and recovers a lower percentage of uranium.

A more recent technique of milling is that of heap leaching. The rocks need only be crushed to about 2 cm. The resultant tailings are larger and therefore more easily managed and require a lower water content.

The waste water is treated to control the metals and radionuclide concentrations to currently acceptable environmental levels. The radionuclides are precipitated and removed with the mill tailings, where they tend to concentrate, particularly radium, with the slime (≤ 10 µm) fraction. Decanted water from the tailings is treated with barium chloride in a precipitation pond.

Of the non-radioactive constituents of tailings, pyrite is a major concern. Upon oxidization it results in the release of sulphuric acid and heavy metals. Neither of these are produced in economically viable quantities. The problem is severe when the acid leach method is employed. In areas of excess water discharge over evaporation, expensive chemical precipitation methods have to be used to avoid the release of radionuclides to the natural water courses.

2.2 Disposal Methods

The method and site of tailings disposal are contingent upon the mining operation, the milling process and environmental considerations. The type of ore body being excavated and the method of mining are important variables associated with the mining operation which will affect the volume and timing of waste production. The relevance of the milling process has already been discussed with respect to the physical characteristics of the resultant tailings. Environmental factors should be discussed under three broad headings of geology, hydrometeorology and human impact. The first two are relevant to the subsurface and surface suitability of tailing impoundment methods. Six basic types of impoundment are discussed.

2.2.1 Valley Dam Impoundment

The basin for confining the tailings is formed by the construction of an embankment across the headwaters of a small catchment. Generally the tailings are discharged from the embankment or point sources around the basin. Excess water evaporates or is decanted, although a shallow layer of water is desirable to limit the release of radon.

Valley dams are cost effective if the valleys are deep and require minimal dam construction. As the slopes become shallower the surface area to volume ratio of the tailings become high and the management of discharge, particularly the slimes, becomes difficult. Similarly both the dam materials and capping materials, once the operation has ceased, are locally derived and

become expensive as the ratio increases. However steep valley sides induce high hydraulic gradients and increase the transmissivity of the tailings dam and possible effluence through local geological features. This problem is exacerbated by the proximity of local water tables and the presence of alluvium in such locations. Similarly topographic lows are most susceptible to flooding and erosion which may, by virtue of their location, lead to the rapid diffusion of spilled wastes.

2.2.2 Ring Dyke Impoundments

These are generally found in flat-lying terrain and consist of a single self-enclosing embankment. They may occupy a series of low valleys and can be built in multiple stages. The construction of ring dykes tends to be expensive because of the amount of material required, and dam construction techniques are crucial. In favorable locations embankment materials may be excavated from within the storage area which improves the surface area to volume ratio considerably. Lower embankments are required and the hydraulic gradient is reduced. Because of the generally hilltop location, risks of flooding, contamination of local groundwater and rapid diffusion of spills are reduced. The regular shape of the impounded area allows easier management of tailings disposal and the modular nature of the construction permits extra storage capacity to be provided without the additional risk of increasing the height of embankments.

2.2.3 Mine-Pit Impoundment

Old open-cast mine pits can be back-filled with tailings. The attractions of this method are: (1) there are little or no construction costs; (2) no dyke failure; (3) necessary management is minimised and (4) the possibility of erosion of the capping material is low after the closure of operations. A pre-requisite of this disposal method is that there should be a disused pit nearby or else temporary pounding facilities need to be provided until the mining operation digs such a pit. The dewatered tailings may be too voluminous to be contained in the pit, particularly if there is a low overburden to ore ratio. The method is most applicable to dry areas where evaporation from the tailings is rapid. Similarly, a high water table in wet areas deters the physical stabilisation of the tailings and increases the chemical mobility of many of the products of the milling process. Considerable knowledge of rock structure, transmissivity and groundwater fluctuations are required. Mining may have made the pit walls unstable and expensive modification may be required before disposal can begin. Finally, the extent to which an ore body is mined is generally a function of economics rather than its physical characteristics and mining of the remaining ore may in the future become economically feasible. Back-filling of the mine pits would make remining difficult, particularly if the tailings were stored in their saturated

state. The presence of tailings would complicate any future underground mining technique.

2.2.4 Specially Dug Pits

This technique involves the construction of a bedrock disposal pit and the building of embankments from the exhumed material. It combines the advantages of the mine-pit disposal and ring dyke methods in minimising spillage risks and tailings management. Upon completion of the operation the embankments can be used to cover the tailings. However, there may be problems with geologic instability and tailings saturation. More importantly the special excavation of bedrock solely for the disposal of tailings is expensive.

2.2.5 Underground Mine Impoundment

Normally up to 60% of tailings may be returned to the underground mine areas. The coarse fraction of the tailings is separated to provide floors for mining equipment and pillar supports. The fines have to be disposed of in other ways. The exact amount that can be returned to the mine is a function of the ore mineralogy and the type of milling process. Considerations of underground disposal therefore can be subdivided in to the coarse and fine fractions. The majority of the water in the coarse tailings has to be removed before emplacement is possible and it also has to be ensured that the tailings are highly permeable to provide good underground drainage. Ventilation underground generally has to be increased and levels of radon and radon daughter release from the tailing monitored. Future remining may also be hindered by backfilling.

As noted previously a large fraction of the radium, thorium and other contaminants remain in the fine fraction, so that subsurface disposal of coarse tailings does not proportionally decrease the radionuclides at the surface. The absence of a coarse fraction makes disposal difficult as the slime stays in a dense liquid which makes impounding susceptible to erosion and instability.

2.2.6 Deep Lake Impoundment

No mining operation in Canada as yet uses this technique. Tailings would be pumped to the bottom of a deep lake (i.e. a lake with a hypolimnion) to reduce the amount of free oxygen available to react with the tailings. Upon closure of the operation either a man-made or natural layer of sediment will develop over the tailings providing a capping layer.

2.3 General Control Measures

In all the methods of disposal that have been outlined the

primary concern has been the impoundment of liquid/tailings mix and the reduction of seepage of chemically and radioactively contaminated waters to the environment. Natural and synthetic liners have been developed to reduce the transmissivity (permeability divided by barrier width) of embankments or natural impoundments. Chemical barriers are used to eliminate radioactive seepage while allowing the relatively pure water to enter the hydrosphere.

2.3.1 Geologic Liners

Wherever possible, local impermeable geologic formations are employed at least in part of the impoundment area. Their thickness and stability in local conditions lend themselves to good long-term containment given the absence of permeable faults and joint systems. Imported geologic liners, notably bentonite, have very low permeabilities and their cation exchange abilities retard the dispersal of contaminants. At low pH's the sodium ions in the clay structure may be exchanged but this disintegration can be avoided by the addition of other chemicals. Clay thicknesses vary from 0.5 m to 1.0 m, but there are frequent difficulties in packing the clay liners.

Thin synthetic membranes (0.5 to 1.5 mm) appear to effectively reduce transmissivity during the period of operation of the uranium mill plant, particularly if used in conjunction with natural liners. There is concern over their longer term suitability. The membranes are susceptible to chemical attack, and differential settling in the tailings may lead to shearing.

2.3.2 Control of Hydraulic Gradient

Reduction of the quantities of water behind the selected impoundment reduces the hydraulic head and therefore the rate of seepage. Drainage may be installed within the impoundment, or water inputs from natural sources and the milling processes may be reduced. The installation of gravel, drains, filter fabrics and pumps is expensive and thus control of incoming sources is usually carried out.

2.3.3 Tailings Management

Considerations of many of the hazards in the disposal process are related to the physical properties of the mine tailings. Four common management practices have been employed. Saturated slurries with greater than 60% water have been deposited below lake surfaces. The tailings form well mixed horizontal layers which become stabilised and reduce the release of radon gas. However, the high percentage of water leads to problems of seepage and the construction of seepage collection systems below the impoundment. Wet management practices release a similar tailings mixture from the embankment. This leads to

the separation of the fine and coarse fractions of the tailings with the sands forming a sloping beach closest to the discharge point. Wind erosion can affect the beaches while the slimes become difficult to rehabilitate because they are incompletely consolidated and the water table is high.

Semi-dry management reduces the water content of the tailings after the milling process and discharges form a ring around the impoundment. Water is decanted from the centre of the pond and treated separately. Problems of wind erosion and radon release are high while seepage concerns are reduced. Water may seep to the surface of the tailings bringing about an internal vertical sorting and possible fine crust formation. The crust substantially reduces the amount of re-entry of water from subsequent tailing deposits.

Tailings are either mechanically dried in the mill plant or retransported to a tailings impoundment following evaporation under dry management. The transport of tailings with 18 to 23% water is difficult and at present mines with the capability to employ dry management techniques still convert tailings to a thick slurry. If alternative transportation methods could be found, problems of slimes, seepage and settlement may be eliminated and radon emissions kept low.

2.3.4 Rehabilitation

Following the cessation of mining activities the tailings disposal areas are generally covered to reduce possible erosion and radon release. Often some combination of clay, native soils and riprap is used. Clay coverage reduces radon emissions although when dessicated the clay becomes susceptible to wind erosion. The nature of the heavy clays used and the improvement of their performance following compaction discourages revegetation and thereby aids erosion. Native soils generally have little radon emission reduction capabilities but encourage revegetation by indigenous species. Broken rock or riprap may be placed on the surface of the soil to impede erosion in the short-run while vegetation is re-established and the tailings stabilise. These three types of cover may be combined to provide the desired environmental conditions.

2.4 Possible Effects On A Permafrost Environment

During the period of operation of the mine, immediate hydrologic concerns about the method of tailings disposal will deal with the changes in heat and moisture conditions in the permafrost environment (Fig. I.2.1). **Consideration should be given to both the effect of the tailings on the environment and the possible effect of the physical setting on the disposal method.** The response of the permafrost to changes in snow cover, the addition of overburden and the thermal properties of the

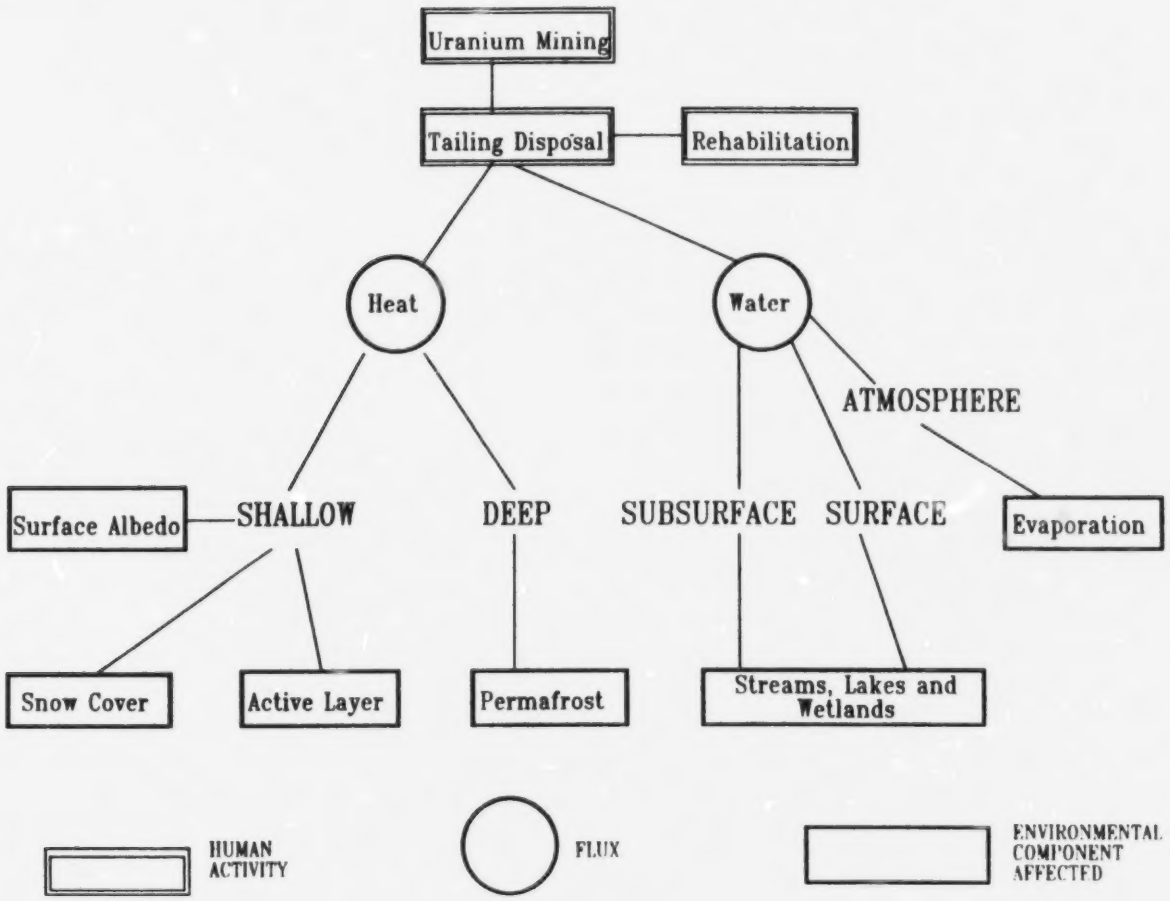


Figure I.2.1: Environmental disruption in a region resulting from uranium tailings disposal.

tailings is crucial. A degradation of permafrost and deepening of the active layer, as observed below large lakes, reduces the efficiency of the retaining structures, seepage increases and the effectiveness of liners is diminished. Stabilisation of the tailings by encouraging the aggradation of permafrost through tailings management practices reduces these problems. However, the seasonal nature of melt and streamflow and the low evaporation in the area create problems for valley dammed impoundments and the control of waste waters. Saturation of the active layer and sparse local vegetation increase the likelihood of serious erosion of both tailings and engineering structures at a time when dispersal of contaminants would be most widespread.

The rehabilitation of the tailings will be difficult. Conventional techniques of revegetation and rehabilitation may not suffice in a permafrost environment as the tailings will be exposed to surface wind and water erosion. Wind in particular tends to carry the radon rich slime fines. Groundwater characteristics of the permafrost are susceptible to changes in the long term and engineering practices designed for permanently frozen ground may prove inadequate as the environmental conditions change.

Should the tailings be impounded behind high dams without adequate provision for dam outflow, a gradual accumulation of water behind the dam may flood the tailings to produce an artificial lake. The thermal regime of this lake will influence the freeze-thaw cycles of the underlying tailings, and may even alter the permafrost underneath the tailings. In this study, only the short-term affects will be simulated because of the lack of data on ground temperatures beneath arctic lake floors.

2.5 Impact Estimation and Regulation

The approach taken in this study is to focus on the tailings. The reduction of the risk of escape of contaminants is best achieved by isolating the contaminants from environmental transport processes. In principle this is simple - surface inflows must be diverted around the tailings, wind erosion must be prevented by covering them, groundwater discharge must be eliminated or contained and treated, and incident precipitation must be evaporated or treated and released. In practice, however, it is necessary to know a great deal about the environment and the changes that the tailings will cause in order to be able to achieve these ends with a certain acceptable risk of failure. The continuing saga of the Niagara Falls, New York waste leakage is testimony to the risks of insufficient study before disposal.

The Keewatin environment in part reduces and in part increases problems compared with the more familiar, more southern areas of previous mining. The presence of permafrost can present

a substrate of very low permeability, but it is subject to disturbance. Precipitation is generally low, but runoff during the melt is high.

For these reasons we have chosen to model the thermal and hydrologic response of the Keewatin environment in a fashion which allows us to predict what changes will occur if the natural materials are replaced with others. As a result we can evaluate different disposal scenarios for their effect on runoff generation, permafrost aggradation or degradation, the water table and other factors.

3. STUDY AREA AND FIELD METHODS

3.1 District of Keewatin

The District of Keewatin consists of the Kazan Upland, the Thelon Plain, the Back Lowland and the Wager Plateau (G.S.C. Map 1254A). (Fig. I.3.1) The Kazan Upland rises to some 600 m, and the Wager Plateau reaches 800 m a.s.l., and these areas have also large local relief. Elsewhere, the relief seldom exceeds 50 m and the elevations are generally below 300 m. Geologically, the District forms part of the north-central zone of the Churchill Structural Province. Much of the area is underlain by Archaean rocks, unconformably overlain by the Aphebian Hurwitz Group that consists of (1) basal conglomerate (2) orthoquartzite (3) slates, shales, siltstones succeeded by dolomite, argillite and siltstone (4) greywacke (5) dirty quartzite. In the Dubawnt Lake area and south of Baker Lake, the Palaeo-Helikian Dubawnt Group with flatlying sedimentary and volcanic beds are exposed. There has been considerable metallogenesis and past commercial mining includes the gold mine at Cullaton Lake, and the nickel mine at Rankin Inlet and the aborted mine at Ferguson Lake. Several areas have uranium deposits with commercial potential.

The entire area has been glaciated recently, with the last glacier ice disappearing only 6,000 years ago. Till characteristics vary with bedrock. Shallow organic deposits are widespread. Various periglacial landforms are found over the entire region, reflecting the occurrence of permafrost. Based on ground temperature data acquired in boreholes, it was found that permafrost reaches 400 m+ at 62° 35.2'N, 98° 38.0'W (Judge et al. 1981). Permafrost depth was estimated to be 60 m at Churchill, 270 m at Rankin Inlet and 500 m+ at Baker Lake (Brown 1978) The active layer is quite shallow, ranging from about 1 m in till and peat, to some 4 m in bedrock.

The occurrence of permafrost is maintained by the cold climate (Hare and Thomas 1974). Mean annual temperature ranges from -10oC in the south to -17oC in the north (Fig. I.3.2). Mean annual precipitation is reported to be about 150 mm in the north, and over 300 mm in the south (Hydrological Atlas of Canada 1978), but these may be underestimates because of the inaccuracy in snowfall measurement (Goodison 1978). Snowmelt is an important annual event for river discharge. The average date for snowmelt peak discharge is mid-June in the south and mid-July in the north. There is a slight hydrograph rise in the fall, possibly due to decreased evaporation at a time when rainfall is still important. In the winter, the large rivers have very low flow while the flow in small streams ceases altogether.

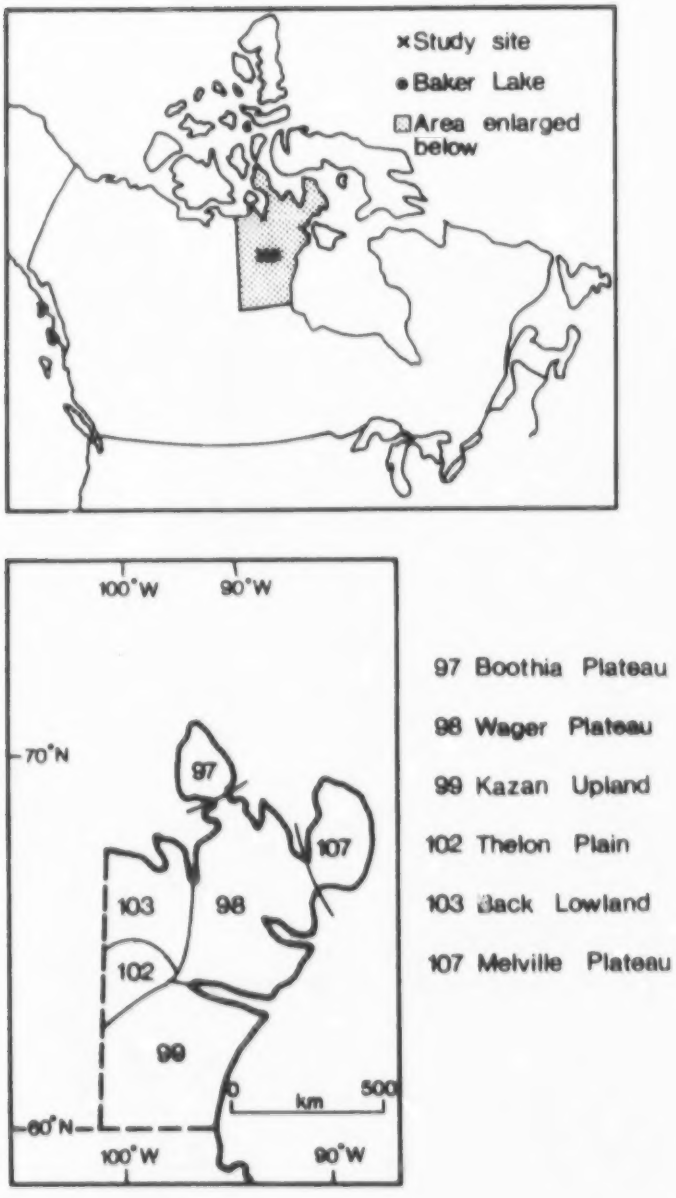


Figure I.3.1: Physiographic subdivisions of Keewatin (After National Atlas of Canada, 1974) and location of field study site.

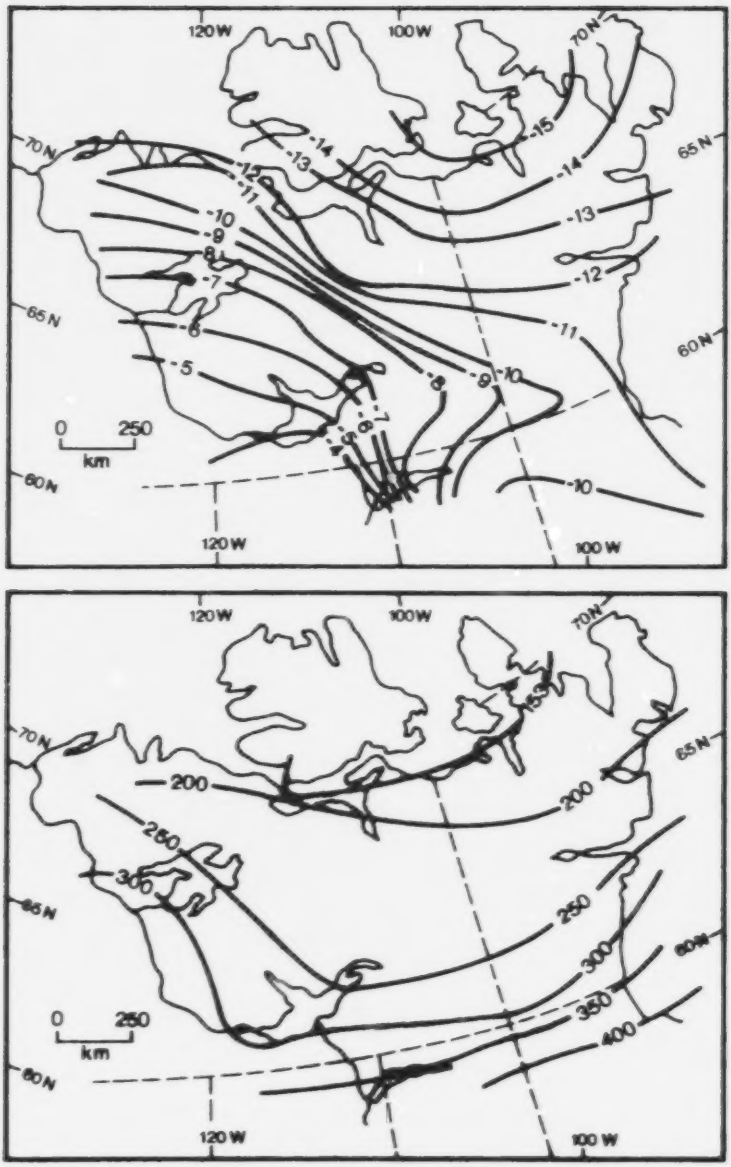


Figure I.3.2: Mean annual temperature in oC (upper) and precipitation in mm (lower) of the District of Keewatin and eastern MacKenzie.

3.2 Lone Gull site

A site in central Keewatin (64o 27'N, 97o 47'W) unofficially named Lone Gull camp, was selected for intensive study to determine the necessary equations and parameter values for the model. This site, located 80 km west of Baker Lake was chosen because (1) it is centrally located in Keewatin, and has all the physical attributes found in most parts of Keewatin, and (2) it is situated near a rich uranium ore body which has a good potential of being developed.

Like other parts of central Keewatin, Lone Gull Camp is underlain by Pre-cambrian rocks. Outcrops of metasediments, including conglomerates, metagraywackes and dirty quartzite, and granite, are exposed in many areas (Fuchs et al. 1982). The entire region was recently glaciated, and red clay-rich till, derived from the red beds of the Dubawnt group (Cunningham and Shilts 1977) covers much of the area. A layer of peat is commonly found on top of the till, but mud-boils, felsenmeer and other periglacial features are frequently found on the slope surfaces. The peat is moderately decomposed and its structure is fabric to mesic.

The study area has rolling topography. Several terrain types are recognized, including exposed flat lands, hilltops, scarp slopes, gentle slopes, bottom lands and valleys, and lakes. Parts of the flatlands, bottomlands and lower slopes are occupied by wetlands. These wetlands owe their preservation to water supplies from (1) lake outflow from upslope, (2) meltwater discharge from late-lying snowbanks, and (3) flooding of streams (Roulet and Woo 1986a).

Like other parts of Keewatin, the Lone Gull area has severe winters and warm summers, with air temperatures remaining below 0oC for over eight months each year. Snowfall constitutes an important portion of annual precipitation but through drifting, the snow is extremely unevenly distributed on the ground. Snow cover can reach great depths below scarp slopes and in the valleys, but is extremely thin on exposed ridge-tops and on the lakes. Rainfall is more uniform spatially, and over the course of a summer, there is only a minor variation in total rainfall between sites. From several years (1979-83) of rainfall and temperature data, it becomes evident that there is considerable variation in the temporal distribution of rainstorms or warm and cold spells within individual years. However, these year to year variations are correlated with those recorded at the Baker Lake station, and this allows the usage of the Baker Lake data in the long-term simulation of hydrological and thermal regimes for sites in central Keewatin.

3.3 Field Methods

Intensive field work was carried out between May and early August of 1982 and 1983 at the Lone Gull site. This field study permitted (1) the identification of major hydrological and thermal processes in the Keewatin environment, (2) the derivation of equations appropriate for the computer model, (3) the determination of the requisite parameter values for the model, (4) the collection of climatic data for comparison with the Baker Lake station (both the field data and the Baker Lake data were used in the simulation studies), and (5) the collection of thermal and hydrological data to verify the model outputs.

Quantities measured were of three main types: surface and subsurface properties of the soils and rocks, manual measurements of hydrological and thermal variables at frequent (daily or once in several days) intervals, and continuous recording of data. Intensive field measurement sites were maintained in a 9 km2 basin. In particular, a wetland and a gentle slope site provided data for model testing.

Four sets of measurements were obtained. The instruments and methods involved are summarized as Table I.3.1.

TABLE I.3.1: FOUR SETS OF VARIABLES AND PARAMETERS MEASURED AT THE LONE GULL STUDY SITE

Variables	Instruments
Meteorological	
Air Temperature	Thermistors recorded on Campbell datalogger
Humidity	Campbell relative humidity probe and datalogger
Wind velocity	Casella-Shepherd anemometers
Precipitation	Tipping-bucket and manual gauges
Snow on the ground	MSC snow sampler
Solar radiation	Kipp pyranometer
Net radiation	Swisstecco net radiometer
Surface albedo	Kipp pyranometers
Surface roughness	Thornthwaite wind profile system
Hydrological	
Slope runoff	Leupold-Stevens type-F water and V-notched weir
Stream levels	Leupold-Stevens type-F water level recorders
Lake levels	Leupold-Stevens type-F water level recorders
Groundwater levels	Leupold-Stevens type-F water level recorders and manual measurements of levels in pits
Lysimeter evaporation	Evaporation pan and lysimeters
Soil moisture	Pre-weighed sample oven-dried for 1 day
Specific yield	Saturated sample gravity drained for 1 day
Hydraulic conductivity	Single well pumping tests
Thermal	
Water temperature	Thermistors
Shallow ground	Thermistors set at various depths
Deep ground temperature	Thermistors installed in bore-holes by Earth Physics Branch, EMR Canada
Frost table depth	Pounding steel rod into ground
Pedological	
Soil profiles	Pit excavation
Soil components	% organic, clastic materials, air and water
Bulk density	Obtain dry weight of samples of known volumes

4. THE COMPUTER MODEL

A one-dimensional model was developed to simulate the daily hydrological and thermal conditions of a vertical profile in the tailings. The major physical processes active in a continuous permafrost environment in which the tailings are emplaced, is shown in Figure I.4.1. All these processes are represented in the model so that any changes in the magnitude and timing of the processes and the effects on the freeze-thaw and water discharge from the tailings, can be reproduced numerically.

The tailings structure is an input to the model. The vertical column is divided into 100 slabs, each of a thickness DZ specified by the user. Individual slabs can be of different materials as specified by the user. Five material types are recognized including bedrock, gravel, fine sand and clay, peat and water. These are materials commonly found in the Keewatin profiles.

Two situations may arise when tailings are disposed in the arctic environment. In the first case, the tailings may or may not be covered by other materials or vegetation but the surface remains dry for most parts of the year except being flooded to a shallow depth (under 0.5 m, say) during the high runoff period. In the second case, the tailings may have been retained by a high dam which then impounds a lake above the tailings materials so that essentially, the tailings are emplaced in a subaqueous mode. These two sets of conditions have to be dealt with separately because of the differences in the physical processes involved.

4.1 Tailings Not Underwater

If the tailings are not flooded, the entire profile will be frozen in winter, and this is a requisite condition for the model. Snow accumulates on the column and the amount of snow on the ground varies depending on the type of terrain in which the column is located. In spring, snow melt proceeds according to the energy supply and the amount of snow storage. Meltwater can infiltrate into the non-saturated frozen soil and will also fill up all the surface depressions. Once the depression storage is satisfied, outflow occurs unless this water is impounded by a tailings dam. An increase in heat supply at the surface also warms the soil, though the presence of a snow cover prevents the temperature of the ground surface from rising above 0oC. The ground will thaw when its temperature gets above the freezing point (which may be < 0oC if the tailings were heavily charged with chemicals during the milling process). Since ice has a volume approximately 1.1 times that of water, thawing of the ice leaves 10% of the soil with voids which need to be filled with water. It is also found that the fractional volume of air in

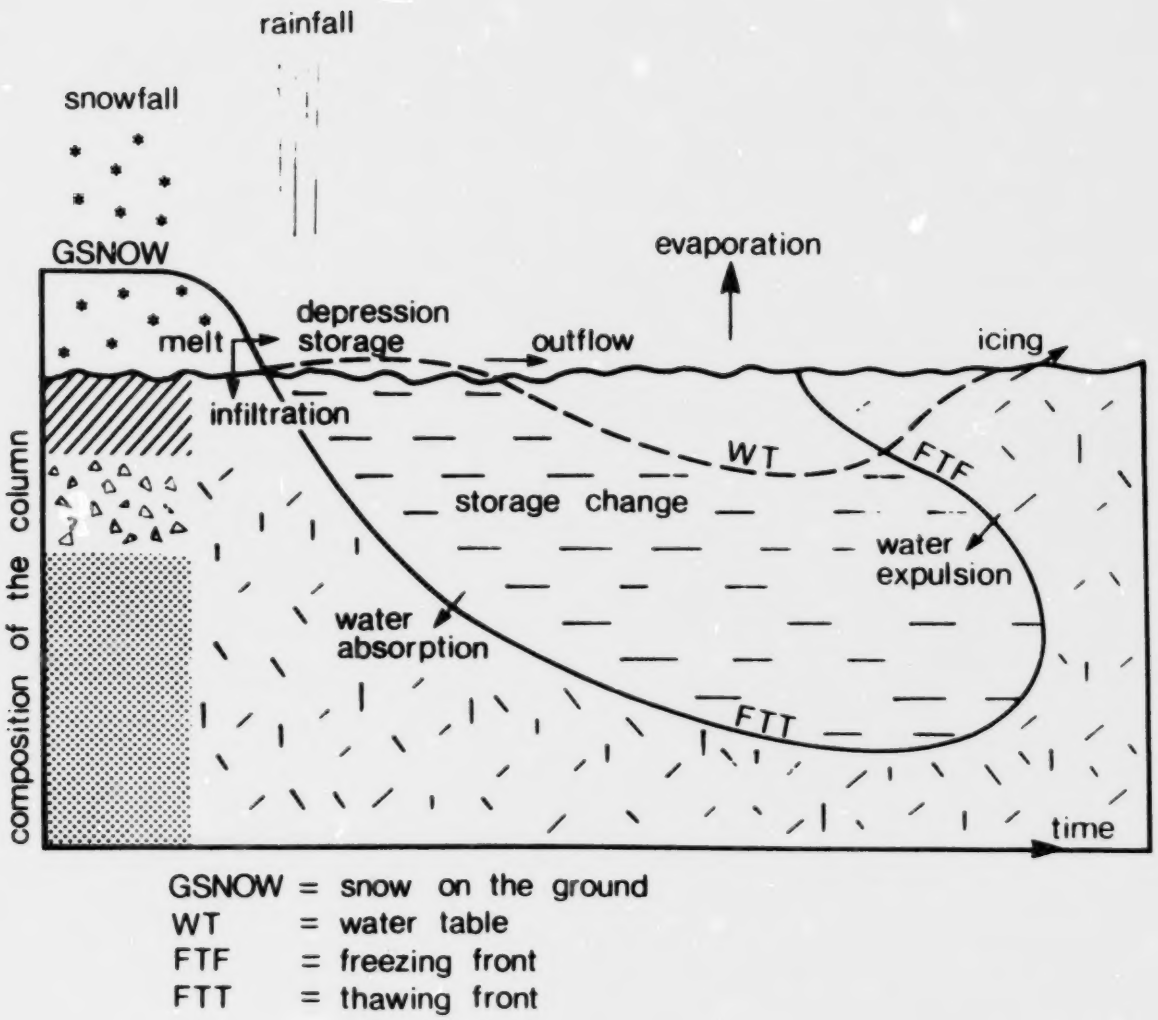


Figure I.4.1: Major physical processes represented by the model for tailings that are not underwater. Of particular importance to tailings management are the frost table (freezing and thawing fronts), the water table, and outflow.

some frozen materials may be different from the fractional volume of air in its equivalent thawed state. The consequences are that water is absorbed by a thawing soil, but expelled from a freezing soil. The latter condition is noticeable in the freeze-back period when the descent of the freezing front may be accompanied by water expulsion to the surface to form icings.

Throughout the thawed season, the column receives water from meltwater, rainfall, inflow from upslope, and loses water to evaporation and outflow. The result of this water balance is a net change in water storage in the thawed zone, which is manifested partially by the position of the water table. The water table defines the upper limit of the saturated zone, but its location is governed by (1) the water balance noted above, and (2) the position of the thawing front below which the column is generally considered to be impervious. Thus, the saturated zone is considered to be perched upon the frost table whose position changes daily as the thawing front advances or retreats; (3) the exchange of water with the depression storage and the gain or loss of water through the freezing (expulsion) or thawing (absorption) of the ground; (4) the amount of water taken up or released by the non-saturated zone above the water table.

When the water table rises above the ground to exceed the maximum level of depression storage, surface outflow occurs. The saturated zone below the water table is prone to lateral subsurface flow. It has been found, however, that subsurface flow is orders of magnitude below surface runoff in central Keewatin (Roulet and Woo 1986b) and that heat flux due to ground water flow is negligible in this environment (McMillan 1983). It is further assumed that an impermeable dam is needed for the tailings to prevent lateral seepage so that groundwater flow at the tailings site is, by all counts, inconsequential. The position of the water table remains as a significant indicator of the potential for lateral transfer of water, and therefore the transport of radionuclides with the water fluxes. Since the water table position and the thickness of the saturated zone are intimately related to the frost table, a coupling of the hydrological and thermal regimes in the permafrost region is the essence of any environmental model pertaining to tailings management.

4.2 Subaqueous tailings

Tailings impounded behind high dams may be subject to prolonged flooding if the water input exceeds water losses through evaporation and outflow (if any). This flood water will give rise to a winter ice cover which will be partially or wholly covered by snowfall. In essence, the tailings pond becomes a small, arctic lake. Thus, the limnological processes observed in the cold regions elsewhere (e.g. Adams 1981, Ashton 1983, Bilello 1980, Hobbie 1973) can be applied to such ponds in the arctic

environment.

Figure I.4.2 depicts diagrammatically the hydrologic and thermal processes occurring above and below a subaqueous tailings column. In summer, evaporation is uninhibited as water is abundant, while the water layer also buffers the tailings from extreme daily temperature fluctuations. In winter, shallow ponds may be frozen to the bottom and the tailings will then undergo downward freezing. Otherwise, the water below a floating ice cover can keep the tailings thawed. The first winter snowfall may be incorporated into the ice as snow slush (Michel, 1971) but when an initial ice cover has been established, the snow will accumulate on top. This snow cover has to be melted in spring before ice decay can begin. Snowmelt follows the same sequence of events as for the non-subaqueous locations: first with melt water front penetrating the cold snow cover, followed by basal ice growth before any meltwater is released from the cover. One modification is where the ice is bottom fast, inducing flooding of both the snow and the ice as melt progresses. In this case, the snowmelt process is dominated by the solar radiation which penetrates the flood water to reach the snow surface. Field observations in the Arctic showed that the fast ice is released from the bottom at about the time when the basal ice of the snow cover is melted (Heron 1985). Once floating, the ice will have little water ponded on its surface because of the many drain holes that commonly develop in the decaying ice (Woodstock and Lukas 1983).

When the ice is entirely melted, the water above the tailings may be lost to evaporation, but other water is gained through lateral inflow and rainfall inputs. Thermally, the water layer is assumed to be thoroughly mixed and the water temperature instead of the ambient air temperature will influence the temperature of the tailings. Should the water be lost entirely from the tailings surface, conditions will be identical to the case where the tailings are not underwater. Otherwise, the tailings will remain saturated and the temperature regime will be modified by the water temperatures.

4.3 Flow diagram for the model:

A flow-chart summarizing the Woo and Drake model is given as Figure I.4.3. The tailings column is built up by the user interactively at the computer terminal. The requisite initial conditions are also set. The model reads from a pre-processed file the daily data for air temperature (°C) precipitation (mm) and solar radiation (MJ m-2) from a base station, and the optional data for inflow to the column (m d-1). On a daily basis, the snow on the ground is updated if necessary, and if the tailings are under water during a cold period, ice growth will be calculated. In the melt season, snowmelt is computed and so is the icemelt, if appropriate.

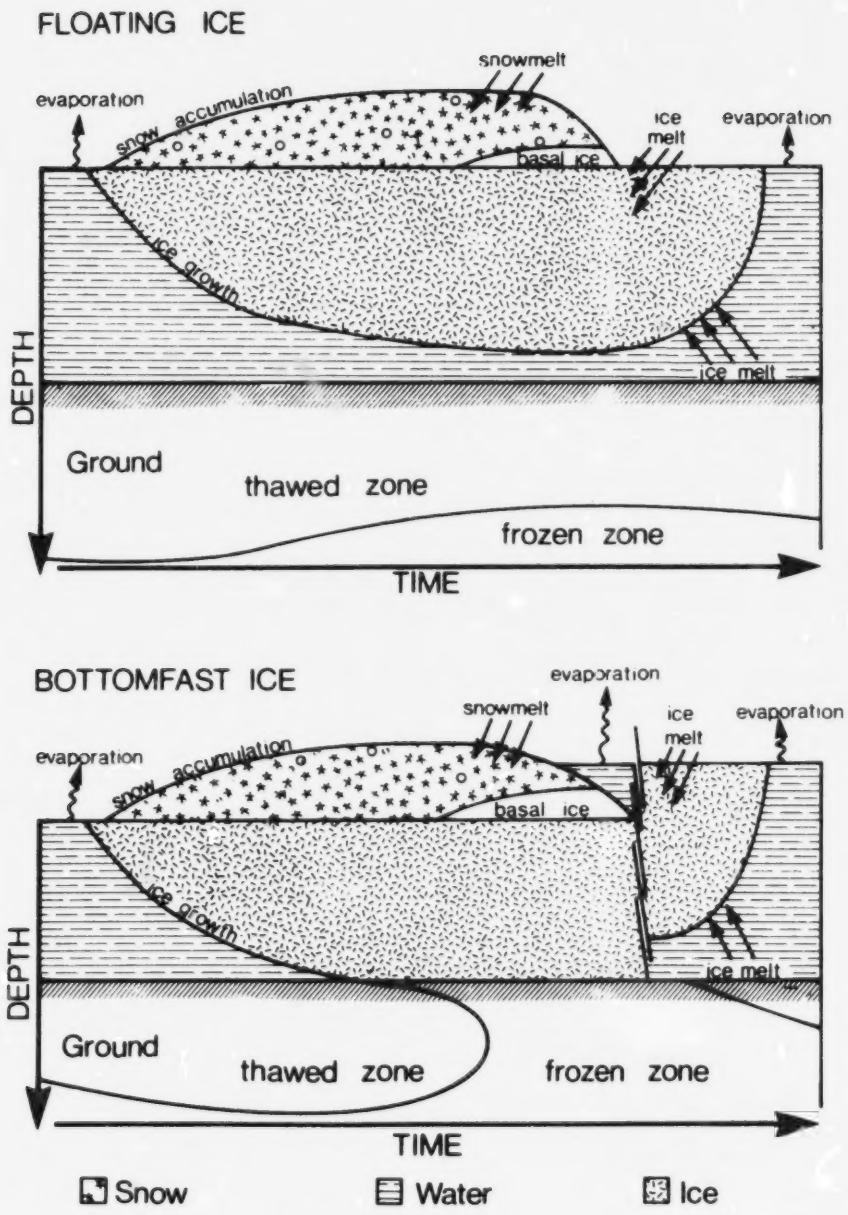


Figure I.4.2 Processes affecting tailings in a subaqueous environment, including evaporation during the ice-free period, ice growth and decay, snow accumulation and melt, and thermal regime of the tailings. The winter ice cover may be floating or bottomfast, depending on the depth of the tailings pond and the severity of the winter.

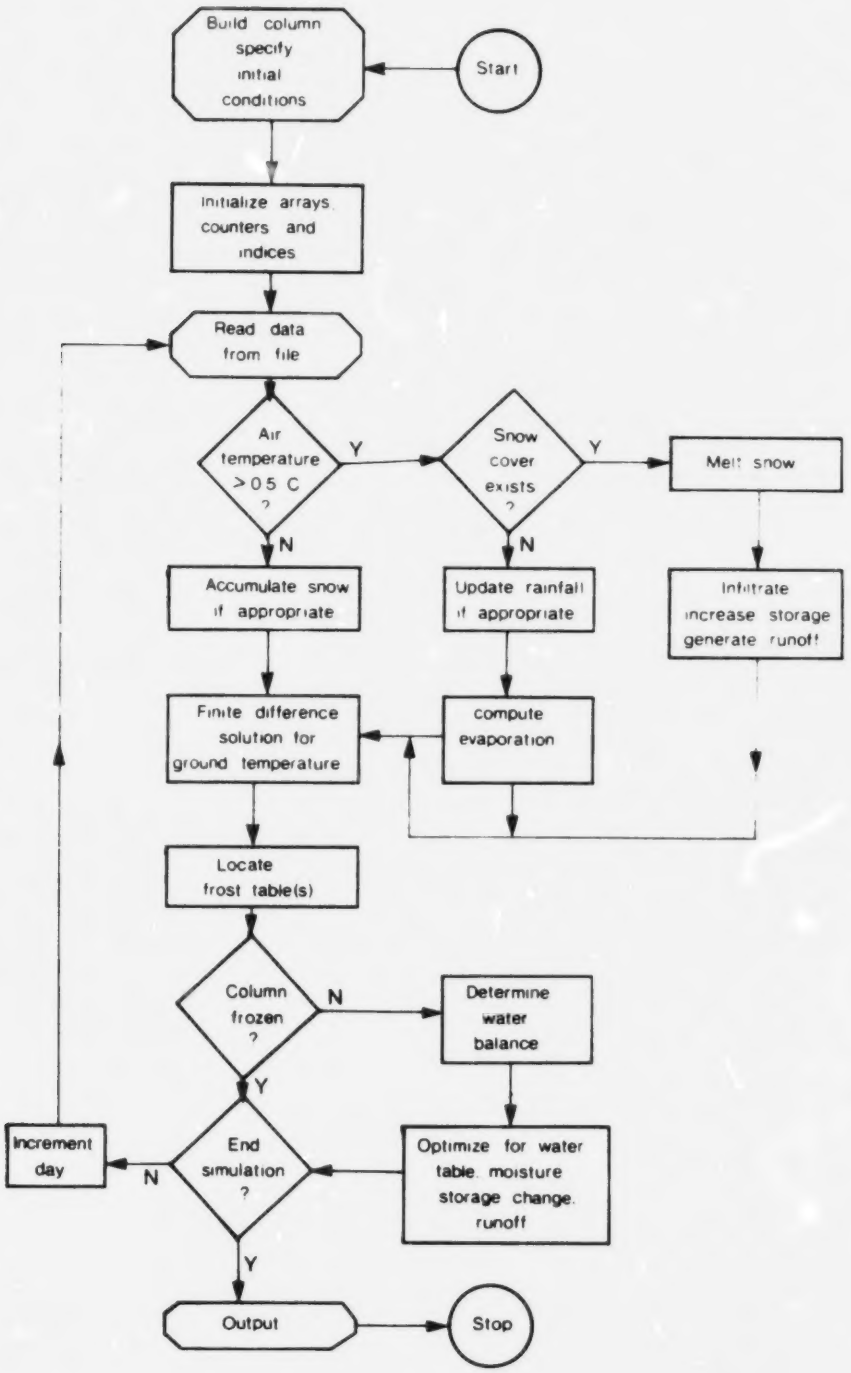


Figure.I.4.3 Flow-chart showing various procedures in the model.

On a daily basis, ground temperatures are computed from a finite difference solution, and this allows the frost table to be determined. Evaporation, water storage and runoff are obtained. These results allow the daily water balance to be performed and the water table position as well as the soil moisture profile are updated. Lateral runoff depends on the amount of surface flow generated and the elevation of the dam to retain this water. Such information, together with the magnitude of all the major hydrological processes, the location of the frost and water tables in the column, and the amount of snow and ice, will be reported for every simulation day. At the end of a simulation year, summary statistics pertaining to the water balance and storage change are also produced.

5. MODEL APPLICATION

5.1 Model Testing

The model was validated against field data acquired between late May and early August in 1982 and 1983 at two experimental sites in the Lone Gull area of Central Keewatin. One site was a wetland with about 0.3 m of peat overlying red clayey till. This wetland received inflow from a lake, mainly during the snowmelt season (Fig. I.5.1). The other test site was a gentle slope with a discontinuous peat layer, about 0.1 m thick, overlying red till (McMillan 1983). This site had no inflow and the measured outflow was small and lasted for only several days in the spring. The daily input climatic data used for the simulation model were obtained from the base camp about 1.5 km east of the experimental sites.

Figure I.5.2 is a comparison of the simulated and observed water and frost tables at the wetland site. The observed frost tables were obtained by hammering a steel rod into the ground until the hard, frozen zone is encountered. A total of 16 plots aligned in two parallel transects were used and the results of measurement are plotted against time in Figure I.5.2 (bottom). There is considerable scatter due to variation between plots. One particular plot, located at the edge of the wetland site, showed notable departures from the general frost table positions of the wetland. Given the uncertainties due to measurement and inherent heterogeneity of the site, the simulated frost table depth agrees reasonably well with the observed trend. The water tables at the 16 plots were also measured and plotted as Figure I.5.2 (top).

Again, there were spatial variations and the simulated water table falls within the range of observed water table positions for the wetland site.

The above test runs were performed using the limited amount of climatic data we gathered in the field. For practical applications, it is necessary to determine the effects of various tailings management strategies over the entire year. This requires data from weather stations which provide information beyond the confines of individual field seasons. Baker Lake station, located 80 km east of the Lone Gull camp, offers such records. The 1982 and 1983 station data for daily temperature, precipitation and solar radiation were entered into the simulation of hydrological and thermal regimes of our wetland site. The two years' results for the frost table and water table positions are given in Figure I.5.3.

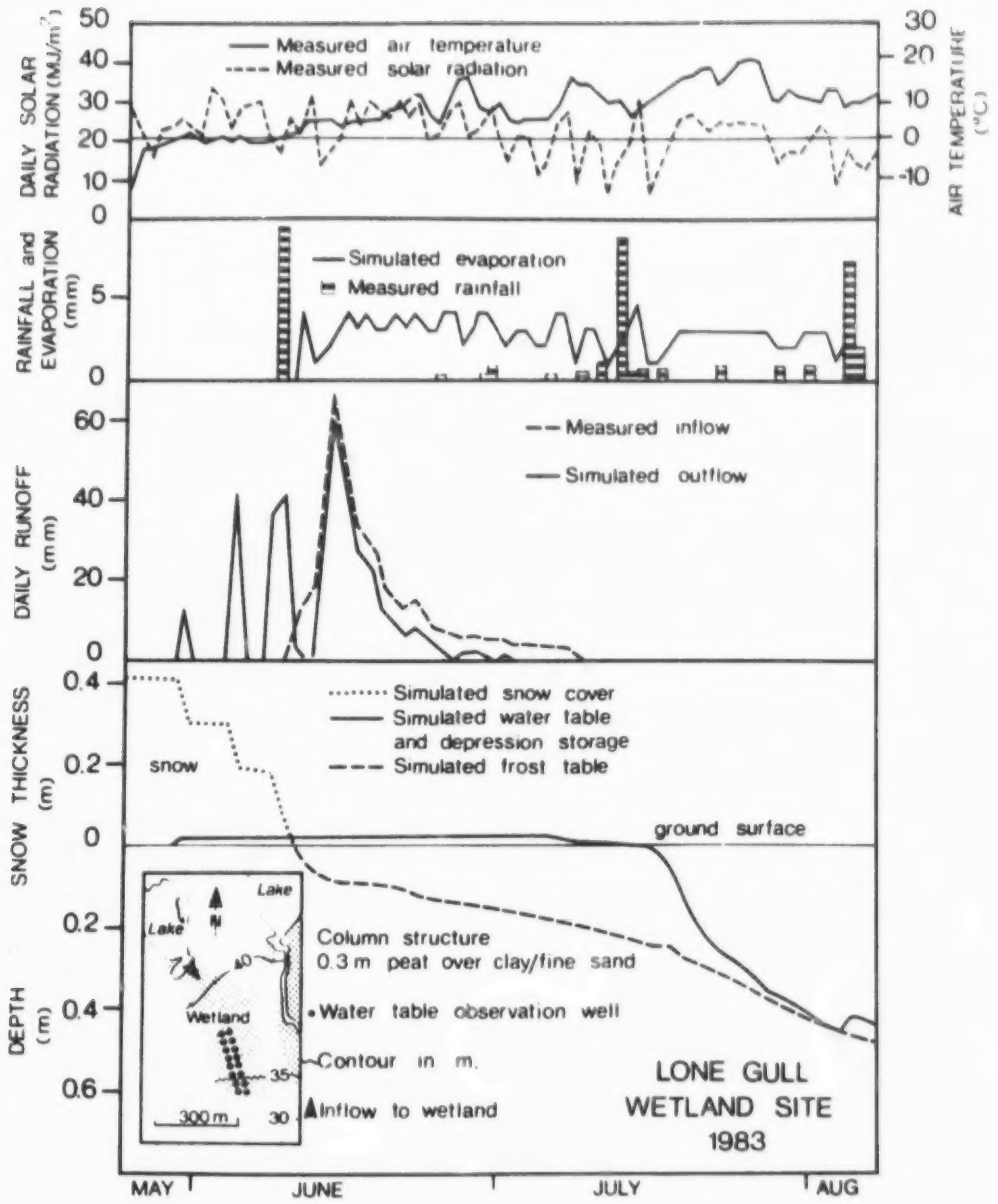


Figure I.5.1: Measured daily air temperature, solar radiation, rainfall and inflow to the Lone Gull wetland test-site (shown as inset). Also shown are the simulated evaporation, outflow, snow depth, water and frost tables.

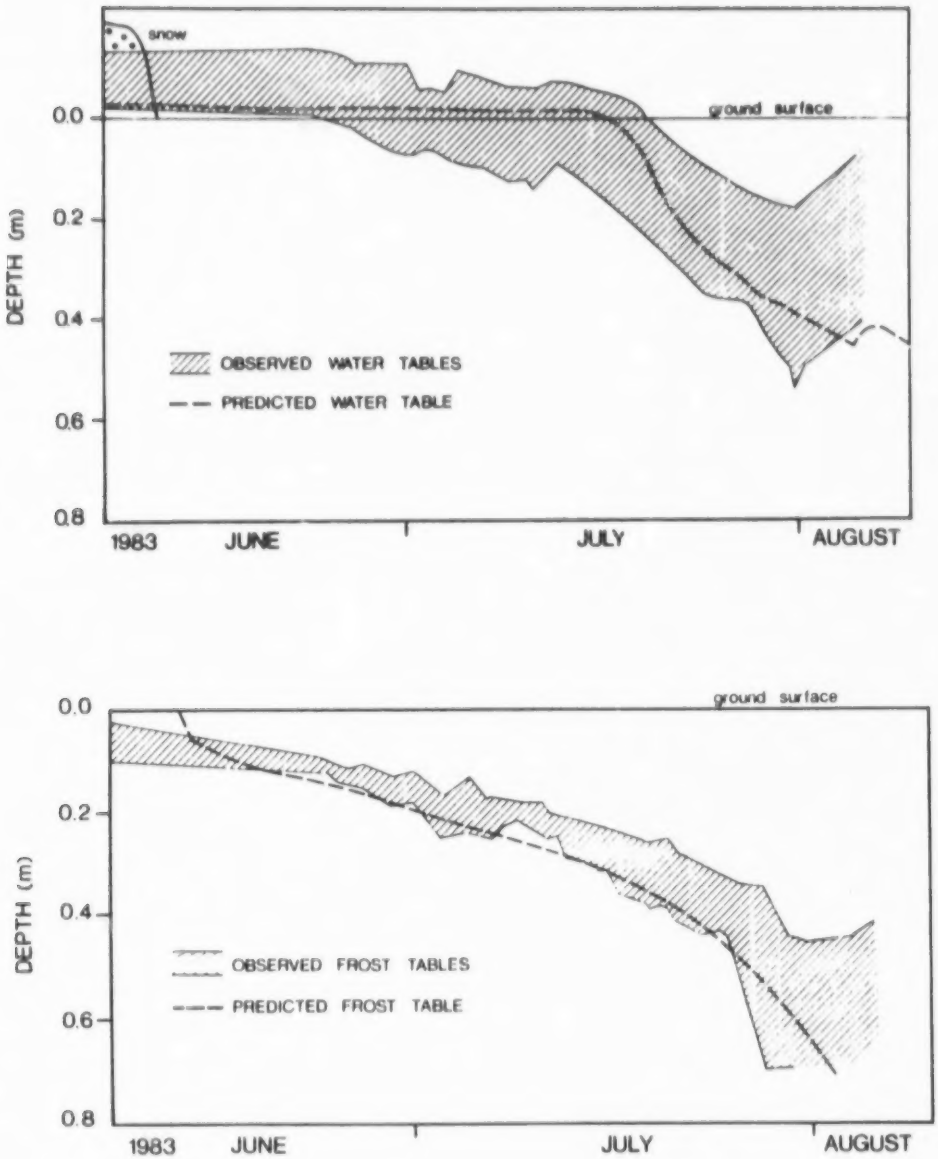


Figure I.5.2: Comparison of simulated and observed water (top) and frost (bottom) tables. The shaded bands show the range of observed frost and water table positions based on the data from the observation wells shown in Figure I.5.1.

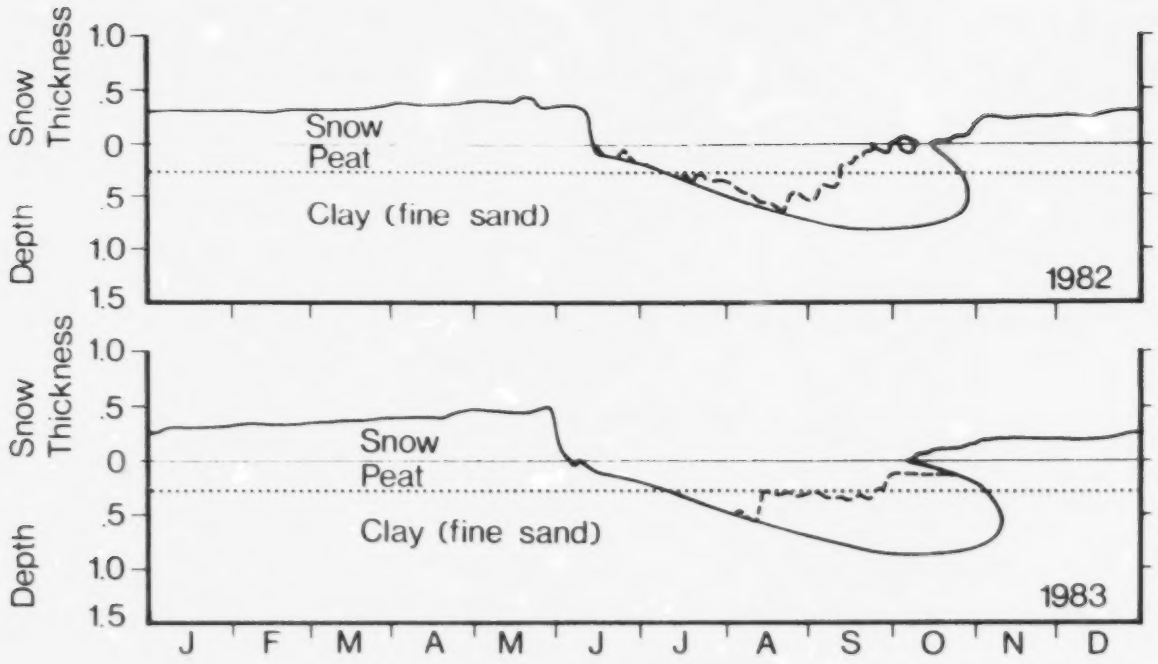


Figure I.5.3: Two years of simulated snow depth, frost table and water table obtained using meteorological data from Baker Lake.

In 1982, a long snowmelt period did not terminate until mid-June, and several rainstorms were distributed quite evenly in the summer. The fall witnessed a sequence of freezing and thawing events but the first snowfall was in mid-September. In the following year, snowmelt was completed by early June and the major rainstorm did not arrive until early August. Freezing was delayed to late September but once it got cold, the air temperature did not rise above 0oC. The simulated frost tables and water tables, plotted against time, reveal year to year differences attributable to the climatic variation. The maximum depth of thaw was slightly greater in 1983, and the length of the thawed period in the ground was extended. The water table was often higher in 1982, reflecting a more even distribution of the rainstorms throughout the summer. The simulations also confirm that in the natural state, the Keewatin soil columns remain frozen throughout winter and most hydrological activities are concentrated in the thawed period. For tailings management, therefore, attention should be focussed within the thawed season.

The lack of data underneath Arctic lakes prevents the verification of the subaqueous phase of the model. The Baker Lake data were used, however, to simulate the ice growth and decay pattern over an assumed tailings that is flooded by about 5 m of water. To ensure that the initial conditions do not affect the model performance, two years of data were repeated five times to produce ten years of input data to the model. It was found that after the first two years the model was not affected by the initial conditions set up at the beginning of the simulation run. Figure I.5.4 shows the lake level, the snow and ice conditions and the frost table position using the 1982 and 1983 meteorological data. The tailings maintained a thawed surface layer because the water was never frozen entirely. The ice formation and decay pattern is similar to those reported for most Arctic Lakes, with a decreasing growth rate as winter continues, but ablates rapidly once the snow cover on the ice is depleted (Heron 1985).

5.2 Effects of Tailings Management Strategies

Regulations can affect the tailings disposal strategies in several ways; each of which can alter the hydrological and thermal regimes of the tailings environment. Prevailing regulations can specify the tailings structure, such as covering the tailings with a gravel layer or planting vegetation on the tailings site. The location of the tailings disposal sites can be specified (e.g. in topographic depressions, or on ridge-tops) and in the Low Arctic situation, the terrain can strongly influence the distribution of snow drifts which, upon melting, deliver a varying amount of water to the tailings. Regulations can also specify the amount of inflow from the basin slopes that is allowed to drain to the tailings site to avoid excessive water

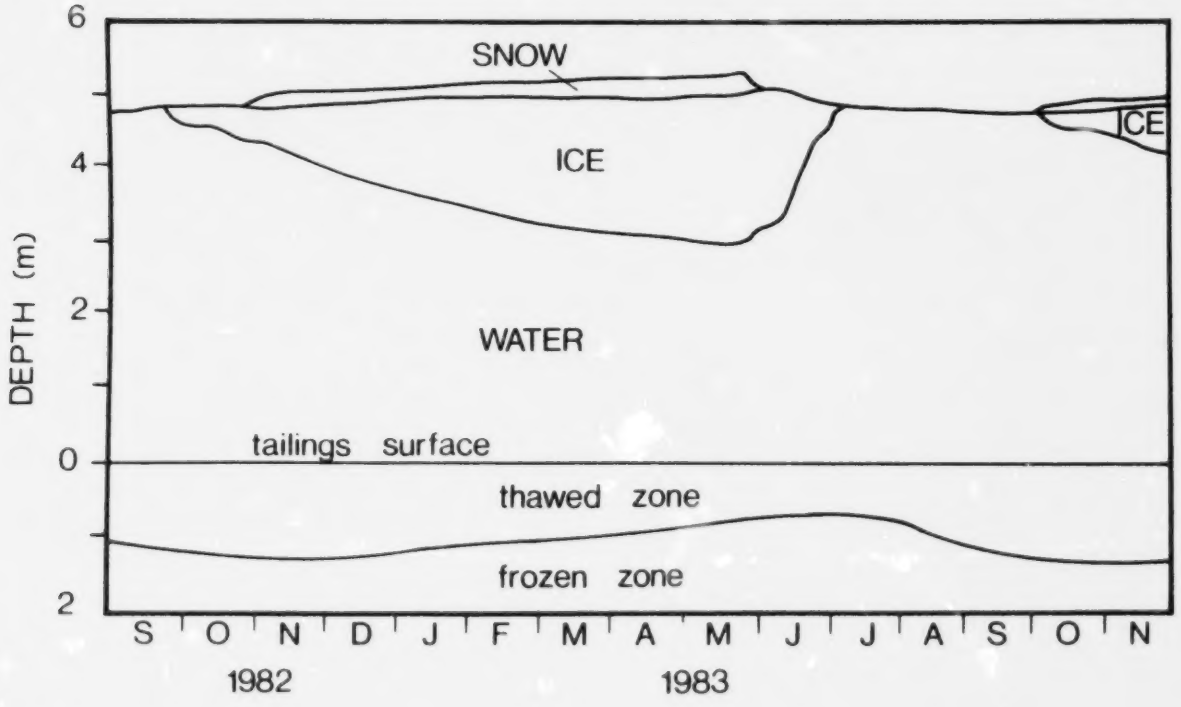


Figure I.5.4: Simulated snow, ice and frost table, using meteorological data from Baker Lake.

input that may overtop the tailings dams. Finally, the minimum height of the dam above the tailings surface can be specified, though the greater the height,the higher the cost will be.

It is desirable to make the tailings disposal measures economical, but it is imperative that the risk of radionuclides escaping from the tailings be minimized. The tailings should be covered to prevent wind blown transport of radionuclides and the outflow from the tailings, both as surface and subsurface flows, should be minimized. The latter can be achieved by surrounding the tailings with impermeable barriers. Since the permafrost can be effectively considered as one such barrier, it remains to seal off the active layer and to impound any surface flow.

The model was used to determine the possible effects of several management strategies upon the thermal and hydrological regimes of the tailings. Of particular importance are the position of the frost table and the water table, and the amount of outflow that is generated. The climatic data from Baker Lake station was again used and, here, the uranium tailings are considered to be composed mainly of fine sand and clay (Fig. I.5.5).

Figure I.5.6 shows the effects of varying the structure of the tailings column while keeping the climatic conditions constant. The Baker Lake data for 1983 were used in this example. The tailings were assumed to be covered by varying thicknesses of peat and gravel, or simply left exposed as clay and fine sand. The total thickness of the column was 5.0 m. The natural soil profile is approximated by 0.3 m of peat overlying 4.7 m of clay and fine sand.

The addition of a thick layer of peat on the clay dramatically reduces the depth of annual thaw because peat acts as a good insulator in the summer but when frozen, the high ice content makes it an excellent heat conductor in the winter. The frozen ground therefore remains shallow and in a similar environment, it has been noted that peat can locally enhance the growth of palsas (e.g. Nelson et al. 1985). In the temperate latitudes, a layer of gravel is added to the uranium mine tailings to reduce surface erosion by wind and by running water (e.g. Madawaska Mines in Bancroft, Ontario). The growth of vegetation on the tailing is also encouraged (e.g. Elliot Lake Mines, Ontario). It is not feasible to regenerate vegetation growth in the Low Arctic environment. Instead, a simulation run was made assuming a layer of gravel followed by peat to cover the tailings. Compared with the natural setting of peat over clay, this treatment produces a similar frost table development but a lower water table when the saturation zone fluctuates within the gravel layer. Another simulation was made, assuming only a gravel layer over the tailings. The frost table then drops

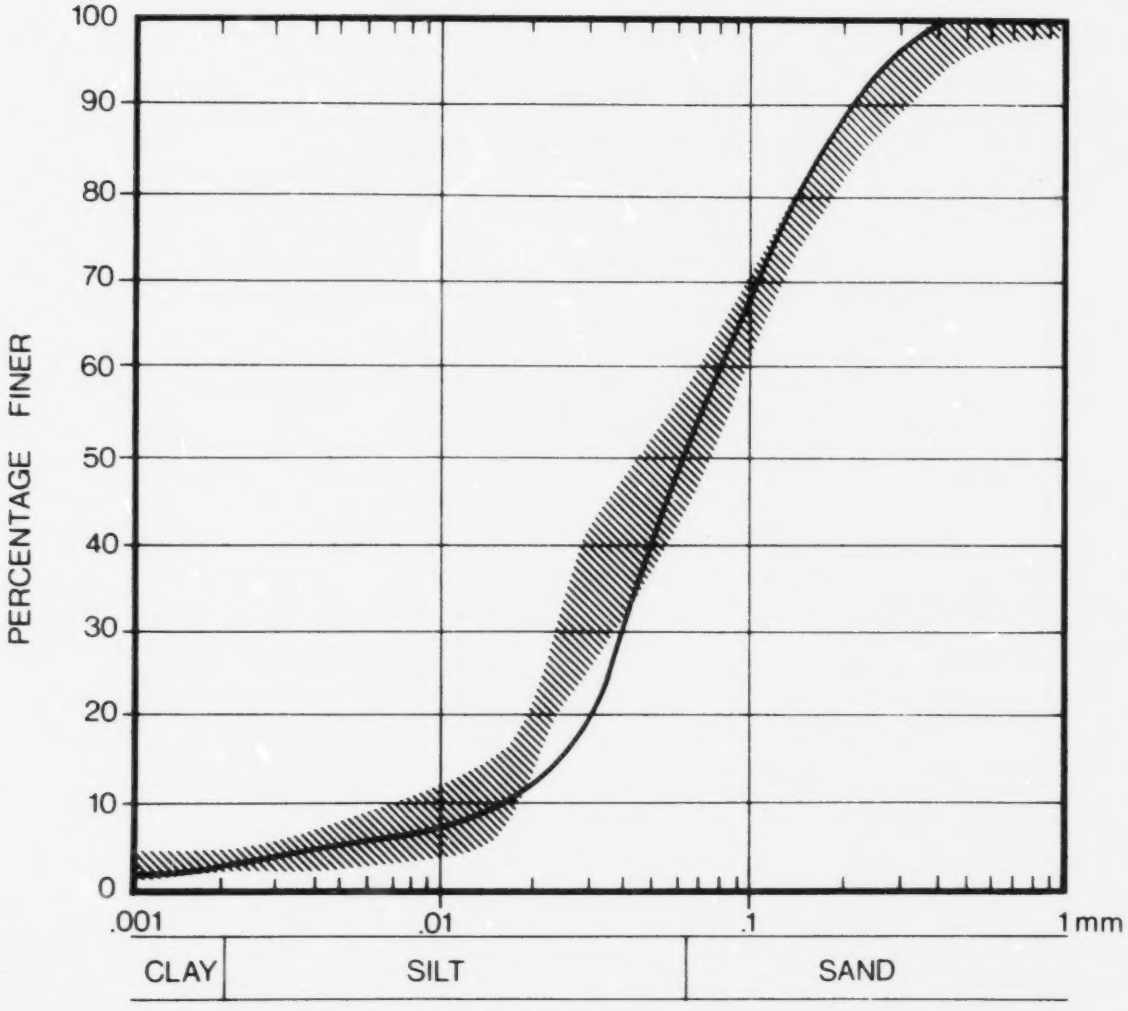


Figure I.5.5: Grain size distribution of uranium mining tailings from Madawaska (line) and Denision mines, Ontario.

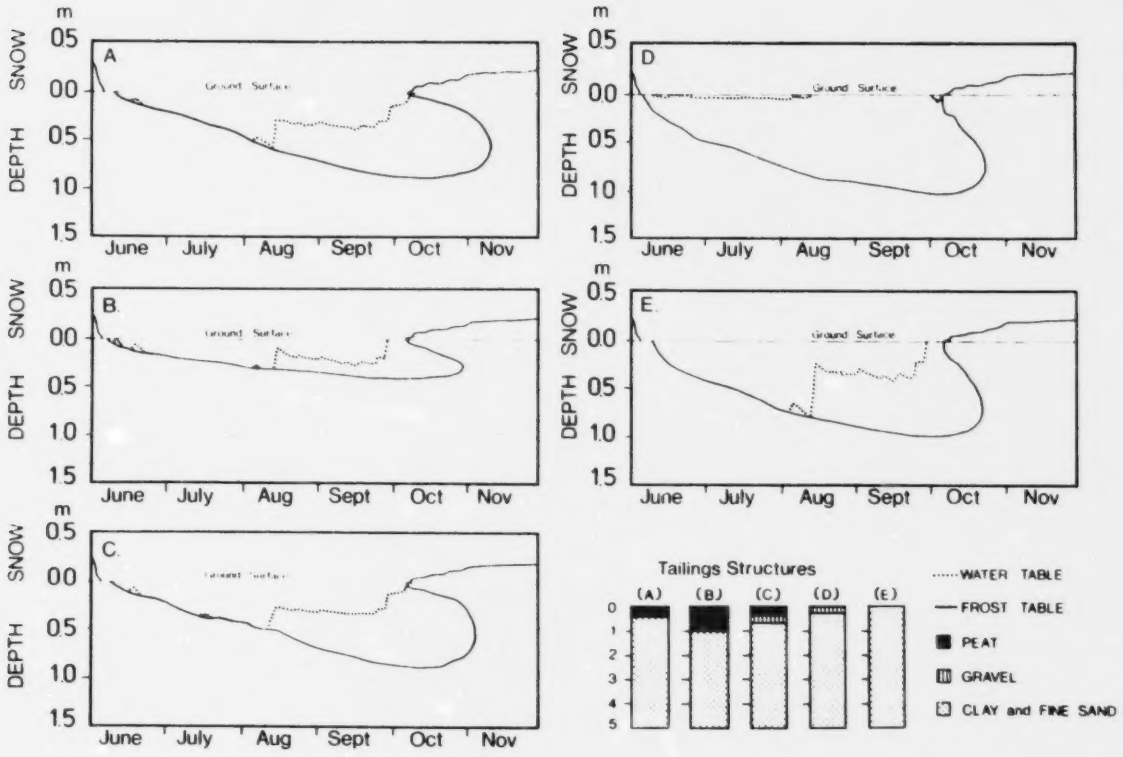


Figure I.5.6: Effects of various hypothetical tailings structures upon the development of frost and water tables, given the 1983 meteorological inputs from Baker Lake weather station.

rapidly in spring and early summer, but the freeze-back was equally rapid. This is attributable to the high thermal conductivity of the clastic materials. This result is similar to that of leaving the tailing uncovered (i.e. clay and fine sand only) but their water table positions are drastically different. Since the gravel has a small capacity to store water, it is either quite dry or saturated. When dry, the evaporation rate is substantially reduced and the water loss is then moderated. Otherwise, the water table is close to the surface and runoff is facilitated.

The effect of altering the amount of snow meltwater input to the tailings is illustrated in Figure I.5.7. Where the tailings are located in flat terrains, the amount of snow drifted onto the tailing was empirically found to be about 1.5 times the station snowfall. Where the tailings are located at the front of scarp slopes, however, the ratio of snow-on-the-ground to the station snowfall rises to about 8.5. The large amount of snow delays the melt season, hence also the first day of ground thaw. A shorter thaw season ensures that the maximum depth of thaw is reduced. The amount of meltwater delivered to the tailings also increases greatly and the surface outflow increases many times.

Other tests can be carried out using the Woo and Drake model. If desired, the freezing point of water can be changed in the model to accommodate the possibility that the tailings are heavily laced with chemicals so that water freezes at temperatures several degrees below 0oC. It is also recognized that climatic changes may take place. The effects of such a scenario can be simulated without substantially modifying the present model. All that is needed is an alteration in the climatic inputs to mimic the temperature, precipitation and radiation trends.

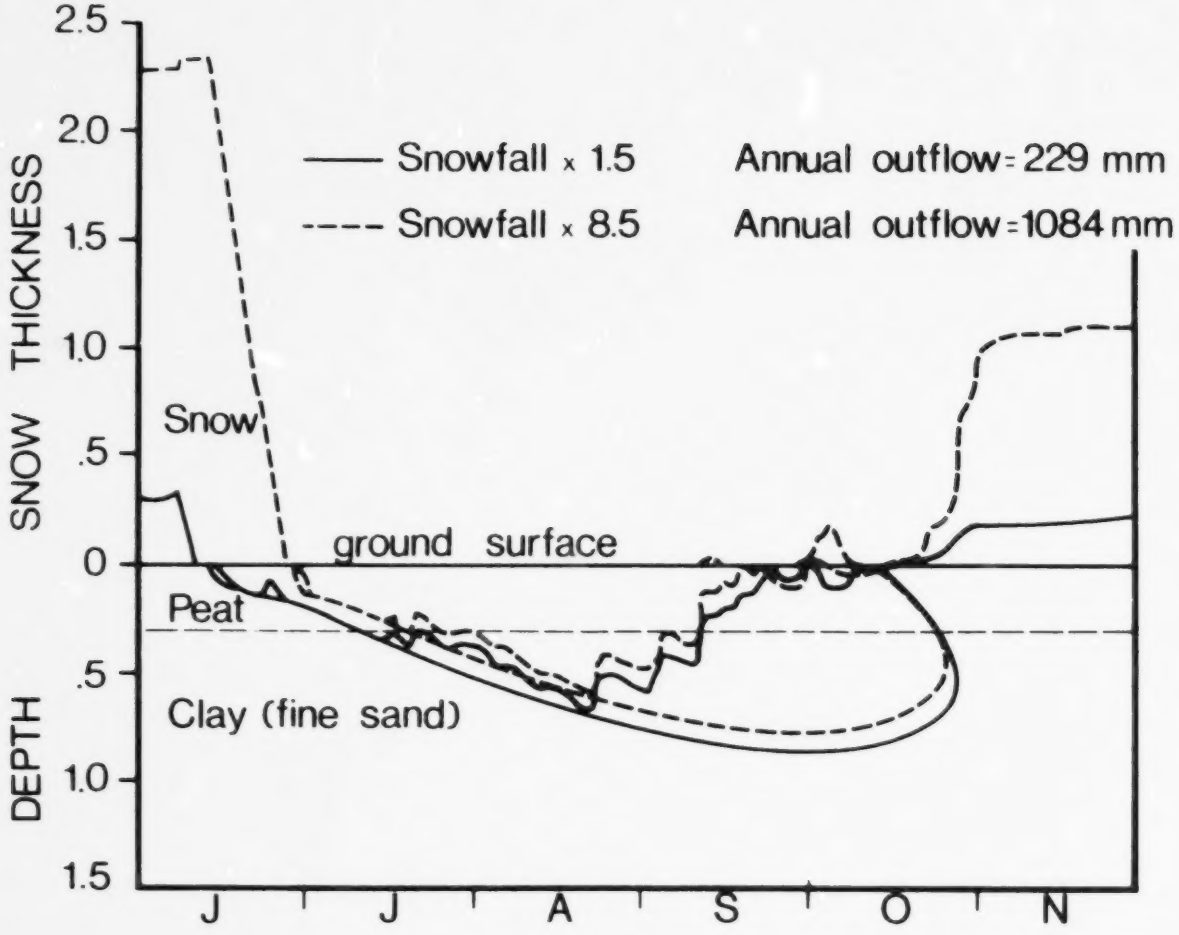


Figure I.5.7: Effects of different amounts of snow meltwater input on the development of frost and water tables and upon the annual outflow. Meteorological data are from Baker Lake and the snow at the tailings sites are 1.5 and 8.5 times that of the 1982-83 Baker Lake snowfall.

6. RECOMMENDATIONS

The results of the model studies indicate that it is possible to design uranium mine tailings disposal strategies that minimize the impact on the land, yet which are not unduly costly. We offer the following recommendations as a result:

6.1 To The Proposing Mining Company:

1. Climatic and hydrologic data must be collected from a proposed mining site for at least two years prior to the beginning of disposal, and surface cover (type, depth, and hydrologic and thermal properties) and terrain (slope, aspect) data must be collected at least one year prior.

   One of the most serious problems in estimating impacts in Keewatin is the lack of data. Two years of climate data is the minimum that will allow (i) the calibration of the model, and (ii) the calibration of the site against the nearest long-run data station that will then allow some estimate to be made of the effects of failure of any approved strategy.

2. The model should be applied to all suggested disposal locations to estimate their impacts, and various types of cover should be evaluated for each.

   Each particular location is different, and data must be collected for each. In most cases a gravel and/or peat cover can be expected to be beneficial, but the feasible depth of cover will also depend on available materials.

3. The model needs further refinement and validation when additional field data become available.

   This is the first model of its kind developed specifically for the permafrost environment where insufficient knowledge and data is available pertaining to the physical processes, the governing equations and the relevant parameters. In the present version, the annual water balance does not close and the subaqueous phase has little data to test against. The model should therefore be improved and further validated to enhance its performance.

6.2 To The Regulatory Agency:

1. The model should be used to determine the general regulations that apply to mining in central Keewatin.

   Certain factors are common to all proposed sites - it is evident that peat is a valuable resource for tailings cover, and so should be stripped and stockpiled before development. Deep snow accumulation is undesirable, and so development should not be so as to encourage it.

2. The model should be applied to each specific proposed tailings site to determine allowable limits and conditions for it.

   Many factors are particular to a site. Different depths of cover or of tailings will have to be defined for each.

3. The model should be used together with a generated long-run data set to estimate the mean time between radionuclide escapes for each proposed tailing.

   By this we mean not the failure of any engineering works associated with it, but rather the escape of radionuclides due to infrequent natural events.

4. The model should be further developed to be able to run for very long hypothetical data sets, and to incorporate feedback to its parameters, to simulate the possible effects of climatic change.

   Permafrost aggrading into the tailings after close-out will be a stabilizing factor. However, the climatic warming predicted by 2050 might be sufficient to change the permafrost regime in Keewatin. The long-term radiological hazard of uranium mine tailings means that long-term changes should be considered.

5. The model could be applied to any mining development in Central Keewatin.

   There is nothing in the model that is specific to uranium mining. It is equally applicable to other metals and mineral tailings, several of which may be equally hazardous.

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